THE EFFECTS OF FREEZING AND THAWING ON PRESTRESSED CONCRETE

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by

F.E. MUSLEH

Joint Highway Research Project

PURDUE UNIVERSITY
LAFAYETTE INDIANA

Final Report

THE EFFECTS OF FREEZING AND THAWING

ON PRESTRESSED CONCRETE

TO:	K. B. Woods, Director Joint Highway Research Project	January 29, 1959
FROM:	H. L. Michael, Assistant Director Joint Highway Research Project	File: 5-13-3 Project: C-36-58C

Attached is a report entitled, "The Effects of Freezing and Thawing on Prestressed Concrete," by Fouad E. Musleh. This report has been prepared under the supervision of M. J. Gutzwiller and was also used by Mr. Musleh as his thesis in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering.

It is anticipated that a paper will be prepared by Messrs. Musleh and Gutzwiller for presentation at the Annual Purdue Road School in 1959.

The report is presented for the record.

Respectfully submitted,

H. L. Michael

H. L. Michael, Secretary

HLM:ac

Attachment

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Final Report

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by

Fouad E. Musleh, Graduate Assistant

Joint Highway Research Project
Project No: C-36-58C
File No: 5-13-3

Purdue University
Lafayette, Indiana

January 29, 1959

ACKNOWLEDGMENTS

The author wishes to express his gratitude to the Joint Highway Research Project at Purdue University, Professor K. B. Woods, Director, who sponsored this study. He is deeply appreciative of the inspiration and assistance of Professor M. J. Gutzwiller, his major professor and of Professor J. L. Waling, Professor of Structural Engineering. He is also grateful to Professor J. F. McLaughlin for his comments and help throughout the study.

Special recognition is due to the Stressteel Corporation for their donation of the steel and the accessories used in this study.

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ABSTRACT

Musleh, Fouad Elyas, M.S.C.E., Purdue University January, 1959. The Effect of Freezing and Thawing on Prestressed Concrete. Major Professor: M. J. Gutzwiller.

An experiment was made with the following objectives:

1. To study the durability of prestressed concrete under repeated cycles of freezing and thawing.

2. To compare the freezing and thawing effects on prestressed concrete and ordinary concrete for specimens made of the same mix giving an ultimate strength of 5000 psi or better after 28 days.

3. To compare the effect of freezing and thawing on prestressed concrete having an ultimate strength of 5000 psi and ordinary concrete specimens made with a leaner mix giving an ultimate strength of about 3000 psi after 28 days.

In all, 48 concrete-beam specimens were made from 8 mixes. Six mixes produced specimens having a minimum ultimate compressive strength of 5000 psi, while two mixes gave specimens having a minimum ultimate strength of 3000 psi. Freeze-thaw deterioration graphs are shown for the individual beams and for the averages of similar beams. Tables for durability factors of individual beams, as well as the average durability factor for similar beams, are presented.

Significant improvement in the durability was found to result from post-tensioning of the beams. Post-tensioned concrete specimens made of a rich mix showed better durability than unstressed concrete made of the same mix and also better than unstressed concrete made of a leaner mix.

Within the scope of this experiment it was observed that unstressed concrete made of the leaner mix was more durable than unstressed concrete made of the richer mix.

INTRODUCTION

In the United States the use of prestressed concrete has now developed to such a stage that detailed information concerning its physical characteristics is urgently needed by engineers.

Prestressed concrete has many new and important applications in Civil and Structural Engineering and offers many advantages. The fine cracks that develop in conventional concrete cannot be avoided. With prestressed concrete the absence of cracks as a permanent feature can be assured up to a maximum loading. The flexibility and resilience of a prestressed concrete structure are also matters of great practical importance. Prestressed concrete members of lesser depths than these required in ordinary reinforced concrete may be employed. This, of course, means a saving in the volume of concrete to be used in a given structure, in addition to the savings in the weight of steel which results from the use of high strength steel bars or wires.

The striking difference in the cost ratio of materials to labor in the United States as compared to some European countries has influenced the direction of the development of this new art. European countries have taken the lead in the use of prestressed concrete on a wide scale. Yet, there is little doubt that prestressed concrete will eventually replace many of the ordinary reinforced concrete structures.

With the birth of this new era of prestressed concrete a new field has been opened for research to study the physical characteristics of this new combination of materials. Many of the qualities of prestressed concrete have been investigated, yet it is believed that the following research work is one of the first to attempt to study the durability of prestressed concrete.

The effect of freezing and thawing on ordinary concrete has been investigated. Woods and Lewis (1)* reported that the effect of freezing and thawing on some materials in a highly-saturated state is a primary factor in their lack of durability in concrete. The absorption and pore or void characteristic of the materials determine their susceptibility to this type of damage. They also reported that the durability of concrete could be improved by drying the aggregates before the incorporation in the concrete and by the use of air entrainment. They recommended these two factors to improve the durability of concrete made of inferior aggregates. Bartel (2) recommended the use of air entrainment to improve the durability of concrete made with poor fine aggregates. He also found that vacuum saturation of aggregates makes them particularly vulnerable to attack by freezing and thawing. He also found that the richer mixes are likely to be less resistant to freezing and thawing than the leaner ones.

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* Numbers in parentheses refer to references appended to this paper.

Pendley (3) used deformed steel bars in the concrete for his experiments on freezing and thawing and allowed a bond to develop between the bars and the concrete. He also employed a steel restraining device around the beam and subjected the beam to a compressive load of 500 psi. Although his arrangement did not directly involve pre-stressing (or post-tensioning) of concrete and the freeze-thaw cycle was between -18 degrees and 135 degrees F, his results shed some light on this research work. He found that:

1. Restraint of concrete decreased deterioration in freezing and thawing. The greatest improvements in durability were obtained with the aggregates having the poorest durability without restraint.

2. Neither the presence of nor the amount of steel reinforcement affected the durability of the concrete significantly.

3. The increase in durability of restrained beams was apparently due to the prevention of cracking perpendicular to the longitudinal axis of the beam. The crack pattern in restrained beams was parallel to the beam axis as compared to a random pattern in unrestrained beams.

Higgs (4) reported that in concrete containing a durable coarse aggregate and with an air content of above 2.5 percent, the influence of fine aggregates on the durability of concrete is negligible. This result was also reported by Walker and Bloem (5) in their studies.

Jackson (6) reported that the durability of concrete subjected to freezing and thawing decreases as the water cement ratio increases. This same result was reported by Hansen (7).

The most acceptable explanation of concrete failure under repeated cycles of freezing and thawing was the hypothesis presented by T. C. Powers (8). This hypothesis presents the action of frost as being the cause of producing hydraulic pressure which tends to cause the deterioration of concrete. This hydraulic pressure depends on many factors, the most important of which is the permeability of the material through which the water must flow to escape from the saturated regions on the surface of a test specimen during the cooling cycle. The degree of saturation and the absorptivity of the test specimens were emphasized as important factors in discussing freezing and thawing of concrete.

Confining our consideration to the cement paste, we know that the freezing and thawing damage is related:

1. Directly to the degree of saturation
2. Directly to the bubble spacing factor
3. Inversely to the tensile strength
4. Inversely to the permeability

At the present time there is no universally accepted specification for the determination of deterioration characteristics of prestressed concrete. The ASTM specification

C-291-52T, "Method of Test for Resistance of Concrete Specimens to Rapid Freezing in Air and Thawing in Water or Brine," was used as a guide in the execution of this research.

PURPOSE AND SCOPE

The purpose of this research was:

1. To study the durability of prestressed concrete under repeated cycles of freezing and thawing.

2. To compare the freezing and thawing effects on prestressed concrete and ordinary concrete for specimens made of the same mix giving an ultimate strength of 5000 psi or better after 28 days.

3. To compare the effect of freezing and thawing on prestressed concrete having an ultimate strength of 5000 psi and ordinary concrete specimens made with a leaner mix giving an ultimate strength of about 3000 psi after 28 days.

The freezing and thawing machine available could accommodate a reasonable number of beams as large as 3 in. x 4 in. x 16 in. A post-tensioning arrangement was used in order to develop the desired force throughout the full length of the prestressed specimens.

Two series of tests were conducted in this study. Two different mix designs were included in each series. One mix design was used for three batches and the other for one batch. Six 3 x 4 x 16-inch beams (and 6 x 12-inch compression test cylinders) were made from each batch of concrete, resulting in twenty-four beams for each series. The results of freezing and thawing tests on a total of 48 beams are thus reported in this thesis.

Series I and II were identical in all respects except the time of curing. Series I was cured for 28 days and series II was cured for 14 days. In each series, mix designs A, B and C were the same and were intended to have a minimum ultimate compressive strength of 5000 psi. Mix design D in each series was intended to have a minimum ultimate compressive strength of 3000 psi.

MATERIALS

Coarse Aggregate

The coarse aggregate (material retained on a No. 4 sieve) used in this investigation was processed in the Joint Highway Research Laboratory. The gravel as obtained met the specifications of the State Highway Department of Indiana for size number 5. The laboratory designation for this aggregate is 2049. The gravel was brought into the laboratory and separated into four gradations: 1 in. to 3/4 in., 3/4 in. to 1/2 in., 1/2 to 3/8 in., and 3/8 in. to No. 4. All material retained on the 1-inch sieve was discarded. The resulting gradation and the physical properties of the coarse aggregate are shown in Table 1.

Fine Aggregate

The fine aggregate (material passing the No. 4 sieve) was local sand (laboratory designation 79-1) obtained from a river terrace deposit. This material met the specifications of the State Highway Department of Indiana for gradation 14, number 2. This sand was divided into two parts--that passing a No. 16 sieve and that retained on a No. 16 sieve. The physical properties of this sand and the gradation used in this study are shown in Table 2.

Table 1

CHARACTERISTICS OF COARSE AGGREGATE (2049)

Dry Rodded Unit Weight	108.8 lbs./cu.ft.*
Bulk Specific Gravity	2.64*
Absorption	1.14 %*

Gradation of Coarse Aggregates

Size	Percent
No. 4 to 3/8 in.	25
3/8 in. to 1/2 in.	25
1/2 in. to 3/4 in.	25
3/4 in. to 1 in.	25

* Previously established laboratory value.

Table 2

CHARACTERISTICS OF FINE AGGREGATE (79-1)

Bulk Specific Gravity	2.61 *
Absorption	1.65% *
Fineness Modulus	3.32 *

Gradation of Fine Aggregate

Size	Percent
Passing Sieve No. 16	66
Retained on Sieve No. 16	34

* Previously established laboratory value.

Cement

Type 1 portland cement manufactured in central Indiana and from a single clinker batch (laboratory designation 315) was used in all mixes.

Air Entraining Agent

Darex was used as an air entraining agent in all mixes. It was diluted, one part Darex to 9 parts water, before being used. Fifty-five cubic centimeters of the diluted agent was used with each cubic foot of concrete.

Water

The mixing water was taken directly from the local water supply. The temperature of this mixing water was somewhat below room temperature when added to the concrete mix.

Steel

The post-tensioning bars were 5/8-inch round steel bars furnished by Stressteel Corporation. The physical properties of the bars are shown in Table 3. End plates and nuts furnished by Stressteel Corporation were used on each post-tensioned beam.

Table 3

CHARACTERISTICS OF STRESSTEEL BARS*

Diameter in Inches	0.650
Original Area in Sq. Inches	0.3254
Yield Strength for 0.2% Offset	45,750 pounds
Yield Strength for 0.2% Offset	140,600 psi
Maximum Load	52,400 pounds
Tensile Strength	161,000 psi
Modulus of Elasticity	26,400,000 psi
Proportional Limit	76,800 psi
Rockwell Hardness Number	28

Chemical Analysis

Element	Percent
Carbon	0.58%
Manganese	0.82%
Phosphorus	0.023%
Sulfur	0.028%
Silicon	2.09%

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* This information was furnished by the Pittsburgh Testing Laboratory and was sent with the steel order.

EQUIPMENT

The equipment used in this study was available in the Joint Highway Research Laboratory and the Purdue University Materials Testing and Structural Engineering Laboratories. Brief descriptions of the equipment are given below.

Concrete Mixer

The concrete was mixed in a Lancaster 1.5-cu.ft. tub-type counter current mixer, powered by a three-horsepower electric motor. The mixer is shown in Figure 1.

Vacuum Saturating Unit

A vacuum saturating unit was used. The unit is capable of vacuum saturating 1.9 cu.ft. under an absolute pressure of 3 cm. of mercury. The unit is shown in Figure 2.

Hydraulic Jacking Unit

A new 60-ton capacity Simplex hydraulic jack with 3 inches of travel was used in the post-tensioning of the beams. The jack had a certified gage calibration furnished by Stressteel Corporation. The calibration of the prestressing unit was checked by use of the 120,000 pound Baldwin Universal Testing Machine in the Purdue University Structural Laboratory to assure the application of the desired magnitude of prestressing force on the beams. With this check on the calibration it was found unnecessary to use strain gages on the bars for load checks. The jacking unit in operation is shown in Figure 3.

FIGURE 1 LANCASTER TUB-TYPE COUNTER CURRENT MIXER

FIGURE 2 VACUUM SATURATING UNIT

FIGURE 3 SIXTY-TON HYDRAULIC JACKING UNIT AND SPECIMEN IN POSITION FOR POST-TENSIONING

Forms

The steel forms, normally used for 3 in. x 4 in. x 16 in-freeze-thaw specimens, were used in this study with some minor alterations. New sliding end plates were prepared with 11/16-in. holes drilled in their centers. Two "C" clamps were used on the ends of the forms to assure the proper dimensions of the beams. The molds were covered with a light film of oil before the concrete was placed. The Stressteel bars were placed through the holes in the end plates and were coated with a lubricant to prevent the development of bond between the steel and the concrete. A typical form used to mold the beams is shown in Figure 4.

Freezing and Thawing Apparatus

In this study automatic freezing and thawing equipment, which had been manufactured and installed by the Carrier Division of the United Clay Products Corporation, was used.

Twenty-five beams can be tested in each of two compartments which serve alternately as freezing chambers and thawing tanks. Refrigeration is accomplished through coils mounted around the perimeter of the two compartments, while two fans mounted above the specimens maintain uniform air temperature in the freezing chamber. A constant 40 degree F. temperature of the water in the storage tank is accomplished by the use of immersion heaters. Starting with the end of the thaw cycle, the temperature is reduced to 0 degrees F. in about one hour. The temperature is maintained at 0 degrees F. for two and one-half hours to allow the centers of the beams to cool to that temperature. The thaw water is then circulated,

FIGURE 4 A TYPICAL CONCRETE FORM

and the temperature is raised quickly to 40 degrees F. The temperature at the centers of the beams reaches 40 degrees F. within 30 minutes after which the water is pumped out in about five minutes. The apparatus thus subjected the specimens to about seven cycles every 24 hours. The timing of each cycle was in agreement with ASTM Specification C 291-52T.

Twice each week or at intervals of about 20 cycles, the apparatus was turned off at the end of a thawing cycle to permit the weighing of the specimens and their testing to determine the dynamic modulus of elasticity.

Natural Frequency Measuring Unit

The natural frequency measuring unit used in these experiments is composed of a variable-frequency oscillator, a variable-frequency driving unit to induce vibrations in the specimen at controlled frequencies, a crystal pickup to detect the frequencies, and a milliammeter to measure the current flow from the pickup. When the induced vibration is of the same frequency as the natural frequency of the beam, resonance occurs and is detected by a sudden increase in the milliammeter reading. Thus, the maximum current flow occurs at the fundamental frequency of vibration of the specimen. The frequency of the induced vibration can be read directly from the oscillator dial. This fundamental frequency measuring unit, which satisfies ASTM Specification C 215-55T, "Method of Test for Fundamental Transverse, Longitudinal, and Torsional Frequencies of Concrete Specimens," is shown in Figure 5.

FIGURE 5 THE NATURAL FREQUENCY
APPARATUS AND SPECIMEN
IN POSITION FOR TESTING

RESEARCH PROCEDURE

Mix Design

The concrete mixes were designed by the b/bo method (9), which is, in essence, the same as the "Recommended Practice for Selecting Proportions for Concrete" published by the American Concrete Institute (10). Mix designs A, B and C were the same and were designed for a 5000-psi strength after 28 days. Mix D was designed for a strength of 3000 psi after 28 days. A four-percent air content was intended for each mix. Each mix was proportioned to give 1.5 cu.ft. of concrete. Trial mixes were used to establish workable concrete of the required strength. Detailed information concerning the mixes is shown in Table 4.

Mixing Procedure

The coarse aggregate in room-dry condition was weighed and batched 24 hours before mixing time. The aggregate was vacuum saturated and left under a constant absolute pressure of 3 cm. of mercury until mixing time.

The fine aggregate was weighed and batched in room-dry condition 24 hours before mixing and was saturated by the addition of water.

The excess water in the coarse and fine aggregates was determined immediately before mixing time by weighing the aggregates when saturated and deducting the original dry weight. This excess water was then deducted from the

Table 4

MIX DESIGN DATA

Mix Designation	Compressive Strength* PSI	Water/ Cement	Sack/ Cu.Yd.	Air Content, Percent	Slump, Inches
1A	6420	.450	6.76	2.5	2.5
1B	5540	.457	6.74	2.7	3.5
1C	5110	.514	6.61	2.3	5.5
1D	3750	.695	4.36	1.7	2.5
IIA	7000	.420	6.77	2.5	1.8
IIB	5600	.445	6.74	2.0	3.0
IIC	5800	.452	6.69	2.5	3.8
IID	3730	.622	4.24	5.25	3.0

* Standard 6 in. by 12 in. cylinders--28 days.

Note: All mixes were designed initially by the b/bo method.

water required by the mix design to determine the required mixing water. The mixing water was made up of two parts--one part included the air entraining agent, the other part was the additional water required to give a slump of two to four inches. The sequence of operations was as follows:

1. The coarse and fine aggregates were placed in the mixing drum and were mixed for one minute.

2. The required cement was weighed and added to the mixer and allowed to mix with the aggregates for another minute.

3. The water containing the air entraining agent was added; then the additional water was poured slowly until a sufficient amount was added to obtain a 2 to 4-inch slump. The mixer was allowed to rotate for at least two minutes, making the total minimum mixing time four minutes.

4. The slump was determined as shown in Figure 6 in accordance with ASTM Designation C 143-52.

5. A gravimetric test was performed to determine the air content. This test was made in accordance with the ASTM Designation C 138-44, except that a 1/10 cubic foot measure was used. This can be seen on Figure 7.

6. The concrete used in the slump and gravimetric tests was discarded.

Molding and Curing of Specimens

Each mix provided enough concrete for three 6 x 12-

FIGURE 6 SLUMP TEST MEASUREMENT

FIGURE 7 ONE-TENTH CUBIC FOOT
BUCKET--FOR AIR CONTENT MEASUREMENT

inch compression test cylinders and six 3 x 4 x 16-inch beams. The fresh concrete was placed in the molds in two layers and each layer was rodded 25 times. A trowel was then passed twice along each side and end of the mold. The mold was then tapped lightly 12 times on each side and 5 times at the ends with a wooden mallet. The surface was then finished with a moistened wooden float.

The molds were covered with a damp cloth in such a way that nothing touched the exposed top of the beam or the cylinders. Heavy canvas was used to cover the cloth in order to assure a humid atmosphere for curing for 24 hours. The beams of Series I and II were then removed from the molds and were stored for 27 or 13 days respectively in a saturated lime solution at about 70 degrees F.

The test cylinders were capped at 24 hours after casting time and were allowed 24 additional hours before they were taken out of the molds and stored in a humid room at 100 percent humidity for an additional 26 days. They were then tested.

<u>Freezing and Thawing of Specimens</u>

At the end of the assigned curing time the specimens were removed from the lime solution, washed, dried and weighed. They were assigned and marked with a letter-number designation as shown in Table 5.

All specimens designated by letters A, B or C followed by numbers 1 or 2 were tested for the fundamental frequency,

Table 5

SPECIMEN MARKINGS AND TEST SUMMARY

3000 PSI CONCRETE	5000 PSI CONCRETE		
Plain Concrete Steel Bar in Center	Plain Concrete Steel Bar in Center	Prestressing Force Released During Testing	Permanently Prestressed Concrete
	A1 A2	A3 A4	A5 A6
	B1 B2	B3 B4	B5 B6
	C1 C2	C3 C4	C5 C6
D1 D2 D3 D4 D5 D6			
6	6	6	6

which corresponded to the zero cycle and 100 percent relative modulus of elasticity. These specimens were meant to represent an ordinary concrete beam made from a rich mix. There was a total of six of these beams for each of the two series. The beams were tested for fundamental frequency about every 20 freeze-thaw cycles and were weighed. Each beam had a steel bar in its center.

All specimens designated by letters A, B or C followed by numbers 3 or 4 were tested for fundamental frequency and were weighed, thus giving zero cycle readings. Then these beams were post-tensioned with a net average stress of 2000 psi on the cross-sectional area. This is the recommended value of .4f'c used in design practice in accordance with Tentative Recommendations for Prestressed Concrete by ACI-ASCE Joint Committee 323 (11). These beams were put in the freezing and thawing machine. The post-tensioning force was released each time before the beam was weighed and tested for fundamental frequency. The original post-tensioning force was re-applied before the beam was put back into the freezing and thawing apparatus. The beams were tested about every 20 cycles.

Specimens designated by letters A, B or C followed by numbers 5 or 6 were post-tensioned to 2000 psi before any readings were taken. This force was left on the beams throughout the entire test period. After the initial force was applied these beams were weighed and tested for the fundamental transverse frequency. They were tested periodically about every 20 cycles.

The six beams designated by letter D and numbers 1 through 6 represented concrete made of a leaner mix for comparison purposes. To accomplish this, the beams were cast with a steel bar in the center similar to the other specimens. They were tested periodically for weight and fundamental transverse frequency at about each 20 cycles of freezing and thawing.

The marking and the tests summarized in Table 5 were duplicated in Series II.

RESULTS AND DISCUSSION

Presentation of Test Results

The number of cycles of freezing and thawing and the corresponding fundamental transverse frequency of each specimen were obtained and recorded during the experiments.

The fundamental transverse frequency is related to the modulus of elasticity by the formula ASTM C215.55T, "Method of Test for Fundamental Transverse, Longitudinal, and Torsional Frequencies of Concrete Specimens":

$$E = C\,W\,n^2$$

where

E = Young's modulus of elasticity in pounds per square inch

W = Weight of specimen in pounds

n = Fundamental Transverse frequency in cycles per second

and,

$$C = .00245\,\frac{L^3T}{b\,t^3}\ \text{sec.}^2\ \text{per square inch}$$

where

L = Length of specimens in inches

b, t = Dimensions of cross section of prism in inches, t being in the direction in which it is driven

and

T = A correction factor

The preceding formula could be used to give a value for Young's modulus, yet in the ASTM Specification 291-52T, "Method of Test for Resistance of Concrete Specimens to Rapid Freezing in Air and Thawing in Water," it is permissible to treat C and W as constants without introducing appreciable error.

Basically, a change in Young's modulus as a result of cycle freezing and thawing can be assumed to represent deterioration of a concrete specimen. It has been recommended that the initial fundamental transverse frequency of the specimen be assumed to represent a Young's modulus (relative 100 percent) to which other frequencies could be related by the formula

$$Pc = \frac{n_c^2}{n_o^2} \times 100$$

where

Pc = Relative modulus of elasticity expressed as a percentage, after c cycles of freezing and thawing

n_o = Fundamental transverse frequency at zero cycles of freezing and thawing

n_c = Fundamental transverse frequency after c cycles of freezing and thawing

Thus, the relative moduli of elasticity were calculated for each specimen after each measurement of natural frequency.

The weights of the specimens were recorded throughout the experiment. Excessive pitting and pop-outs during the experiment, even at early stages, made weight analyses unmeaningful. Limonite was the main deleterious material in the gravel, and it caused most of the damage in this respect.

The durability factor was calculated by the formula

$$DF = \frac{PN}{M} \qquad \text{(ASTM C 291-52T)}$$

where

DF = Durability factor of the test specimen

P = Relative dynamic modulus of elasticity at N cycles, percent

N = Number of cycles at which P reaches the specified minimum value for discontinuing the test or the specified number of cycles at which the exposure is to be terminated, whichever is less

and

M = Specified number of cycles at which the exposure is to be terminated.

For the purpose of this research, the testing of any specimens was to be terminated at 300 freeze-thaw cycles, or when the relative modulus of elasticity dropped to 50 percent.

A curve showing the variation in the relative modulus of elasticity with the number of cycles of feezing and thawing was plotted for each specimen.

Figure 8 shows the results obtained for each individual beam in mix I-A. Since these six beams were divided into three groups of similar specimens, only three legends appear on the graph. The circled figure at the end of each line indicates the number of the specimen. Figures 9, 10, 11, 12 and 13 show similar data for mixes I-B, I-C, II-A, II-B, and II-C, respectively.

Figure 14 is a plot of the average effect of freezing and thawing on the dynamic modulus of elasticity of similar specimens from mix I-A. It should be noted that each curve represents the average results from two similar specimens. Figures 15, 16, 17, 18 and 19 are plots of similar data for similar specimens from I-B, I-C, II-A, II-B, and II-C, respectively.

Figure 20 summarized the results of series I. The values of the relative moduli of elasticity of each six similar specimens were averaged. Likewise, average results from the six similar specimens of mix D in series I were computed and plotted on the same graph for purposes of comparison and evaluation. Figure 21 shows the results of series II in a similar manner. When a specimen was withdrawn from the experiment, its contribution to the average of the group was dropped; and the average for the remaining similar specimens only were computed. To show this on the graphs, a vertical line was drawn through the approximate curve at the last average point taken before the withdrawal of the beams. This will explain

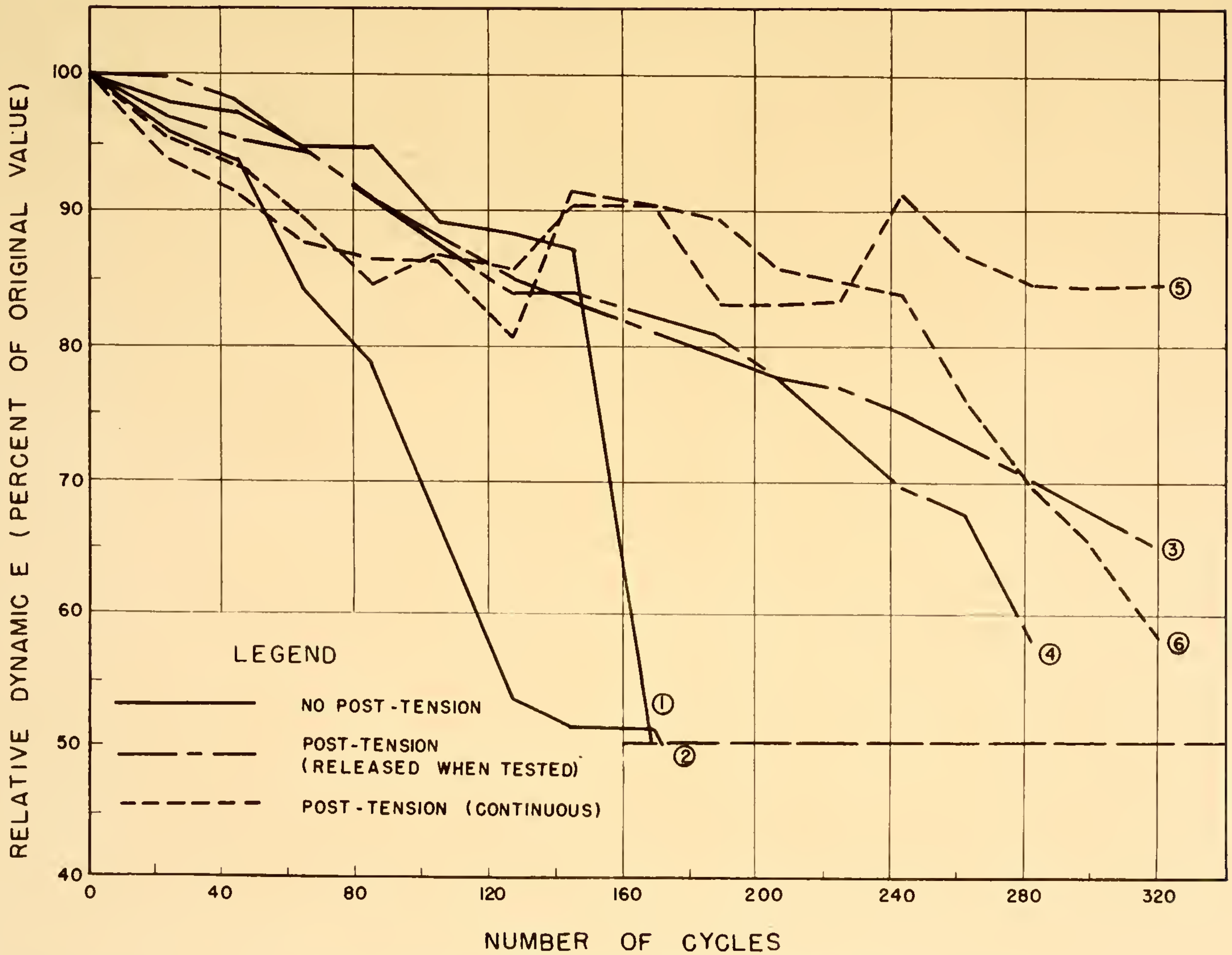

FIGURE 8 THE EFFECT OF FREEZING AND THAWING ON THE DYNAMIC MODULUS OF ELASTICITY. (MIX I A)

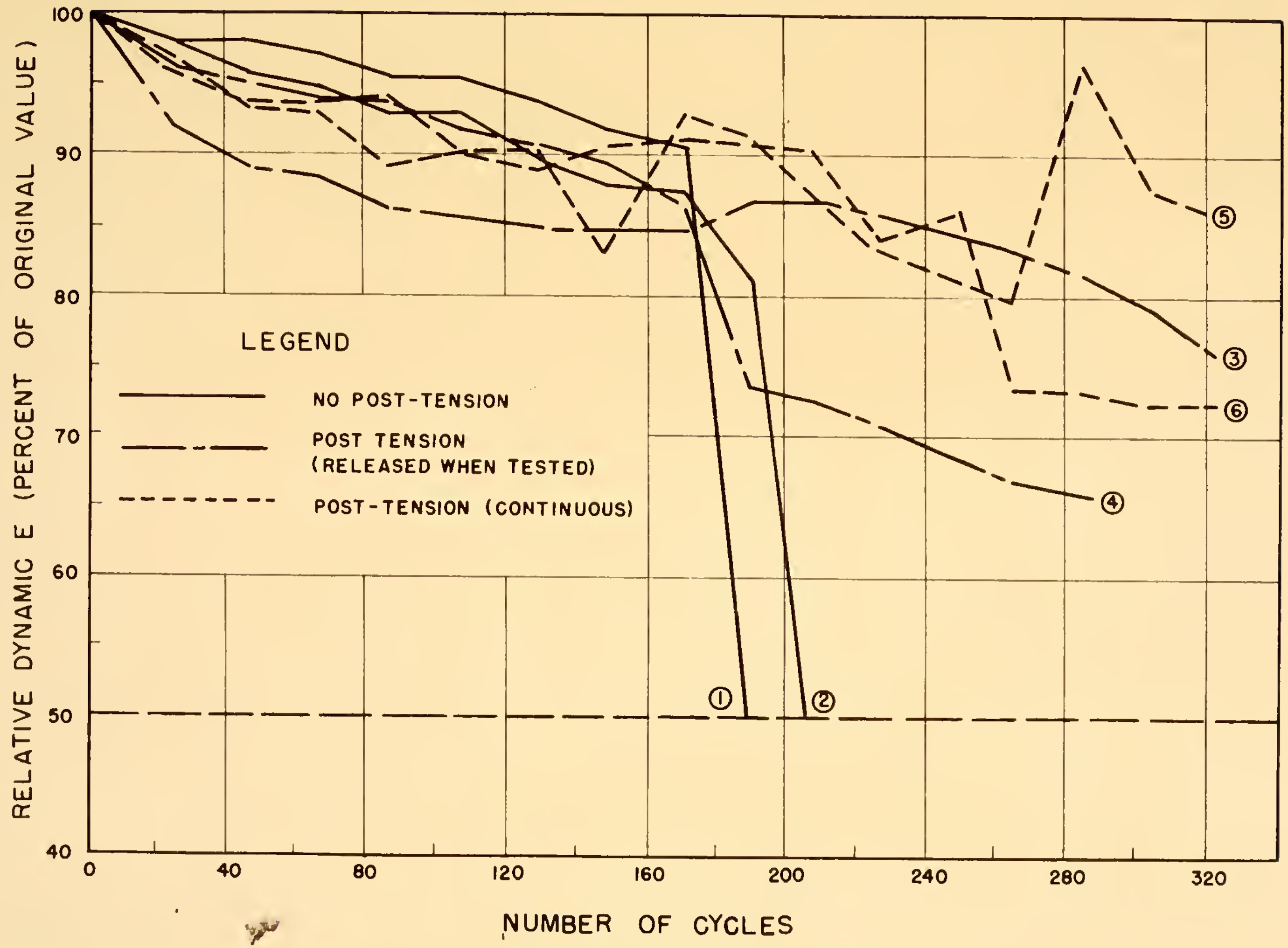

FIGURE 9 THE EFFECT OF FREEZING AND THAWING ON THE DYNAMIC MODULUS OF ELASTICITY. (MIX IB)

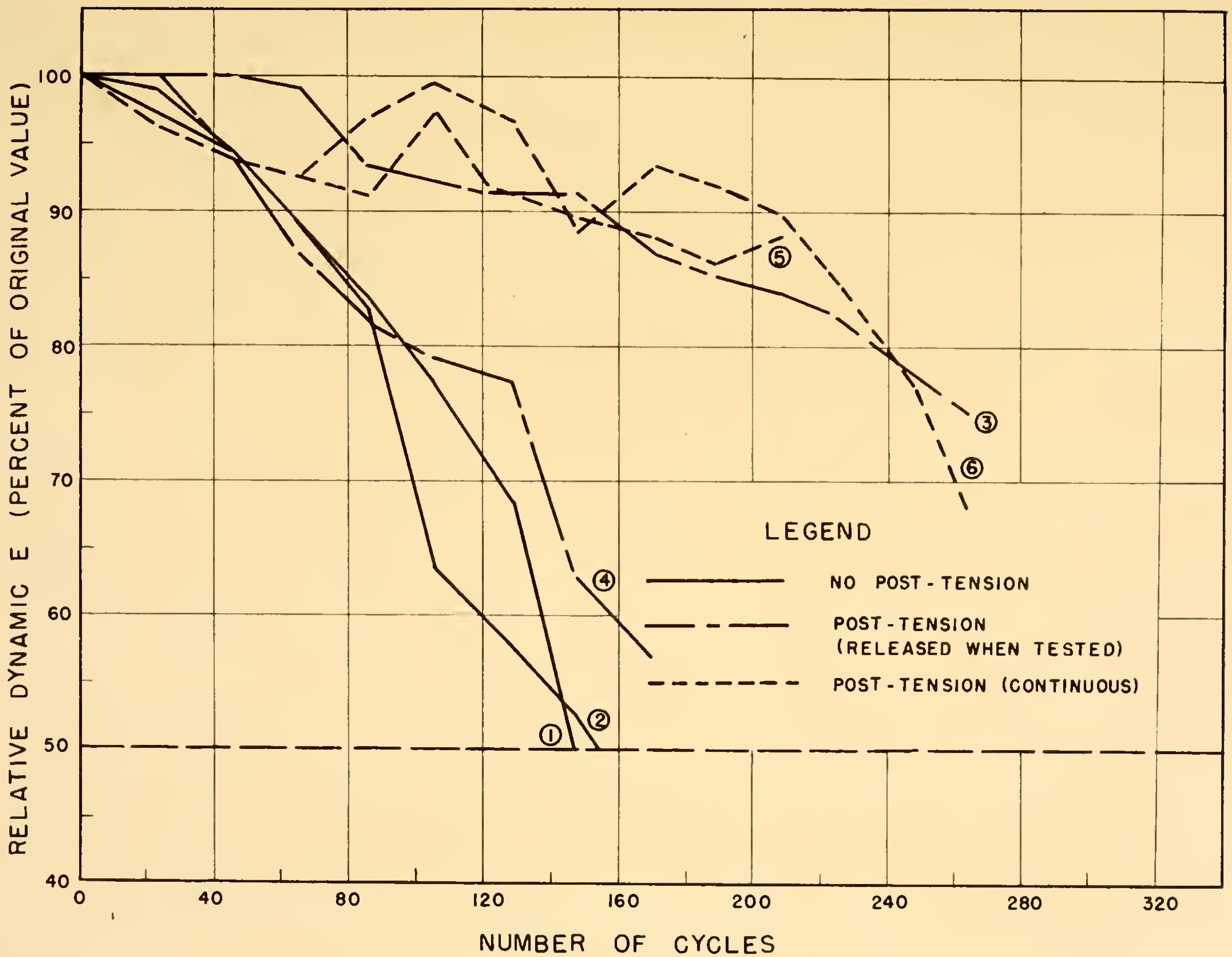

FIGURE 10 THE EFFECT OF FREEZING AND THAWING ON THE DYNAMIC MODULUS OF ELASTICITY. (MIX IC)

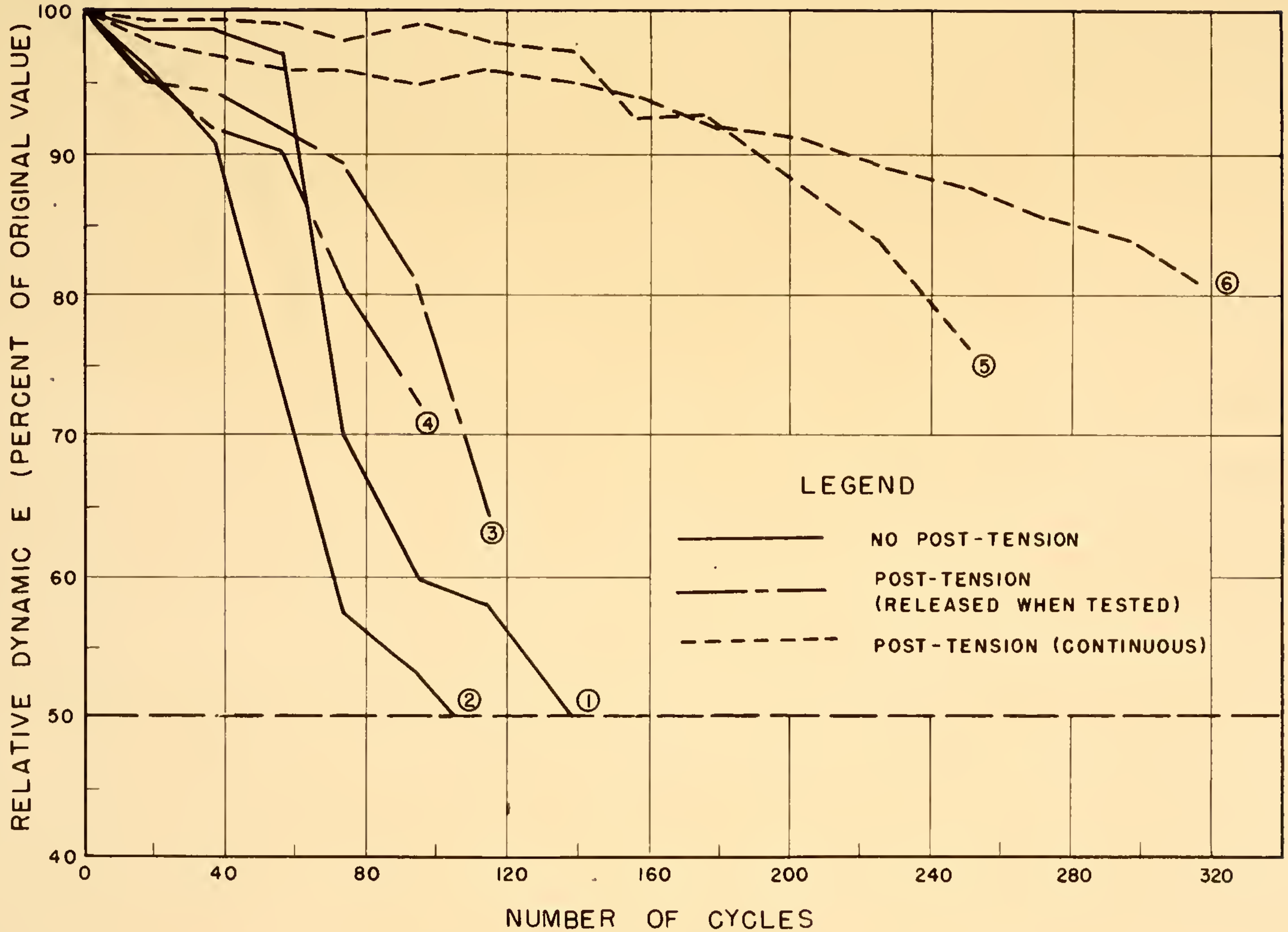

FIGURE 11 THE EFFECT OF FREEZING AND THAWING ON THE DYNAMIC MODULUS OF ELASTICITY. (MIX II A)

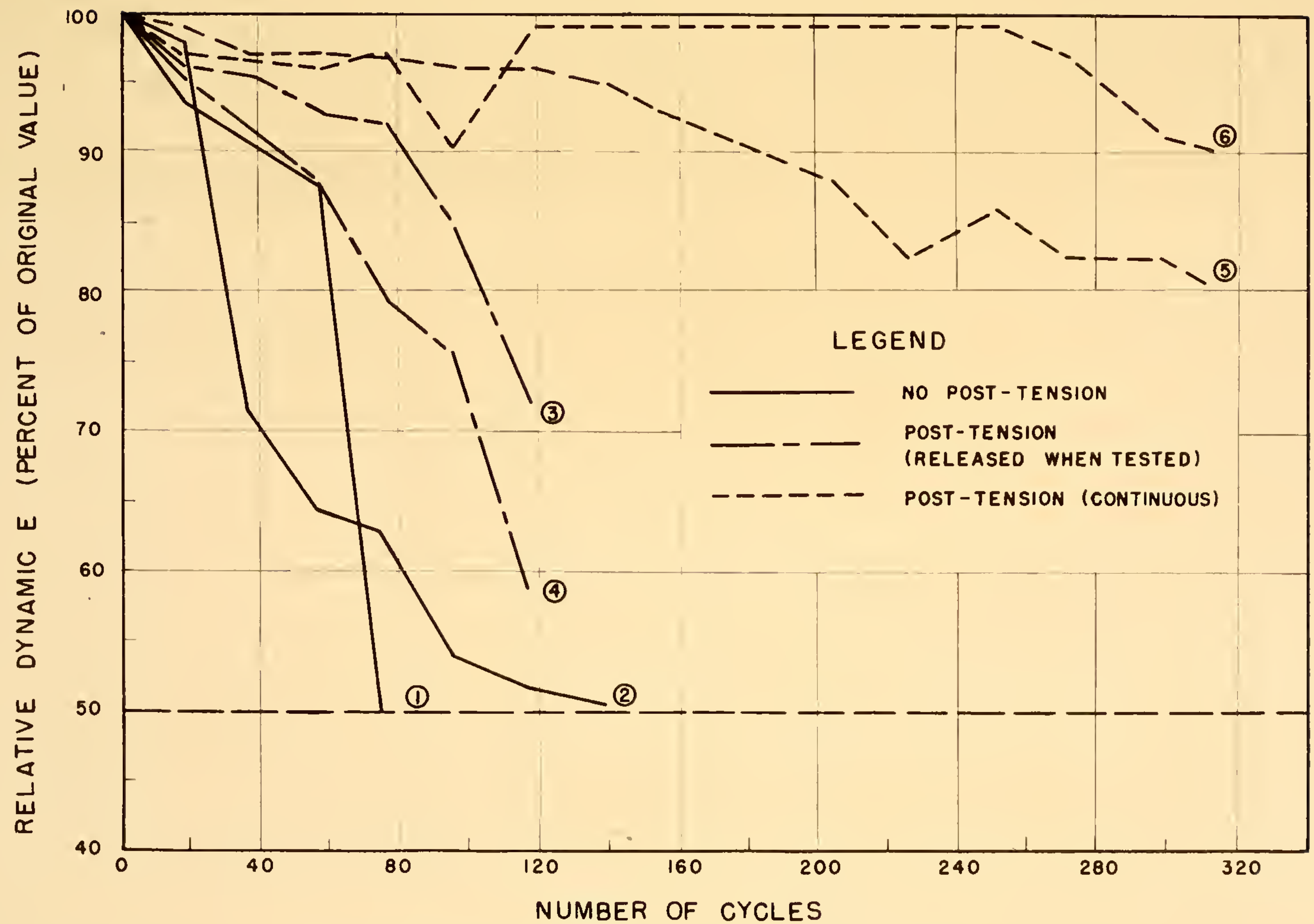

FIGURE 12 THE EFFECT OF FREEZING AND THAWING ON THE DYNAMIC MODULUS OF ELASTICITY. (MIX II B)

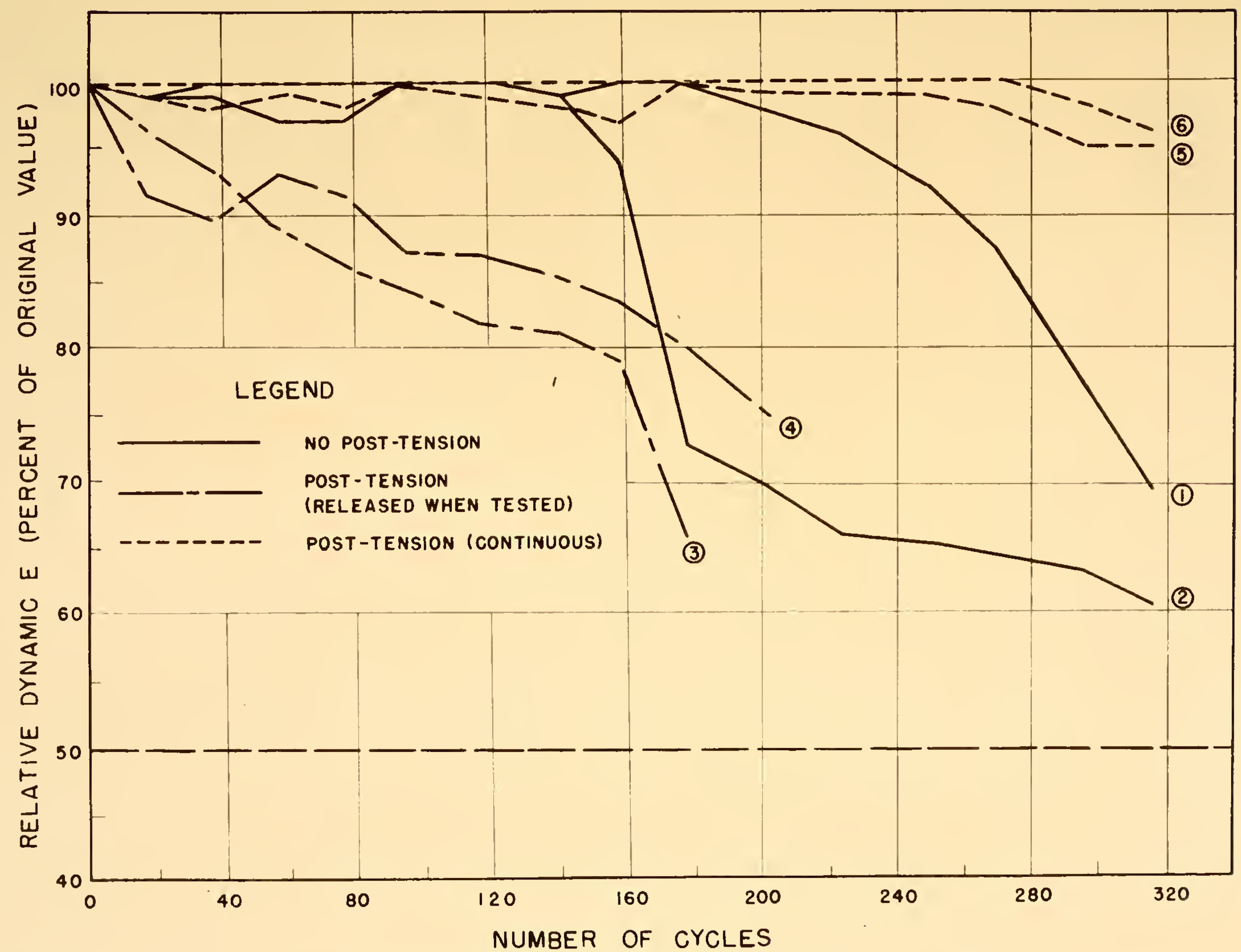

FIGURE 13 THE EFFECT OF FREEZING AND THAWING ON THE DYNAMIC MODULUS OF ELASTICITY. (MIX II C)

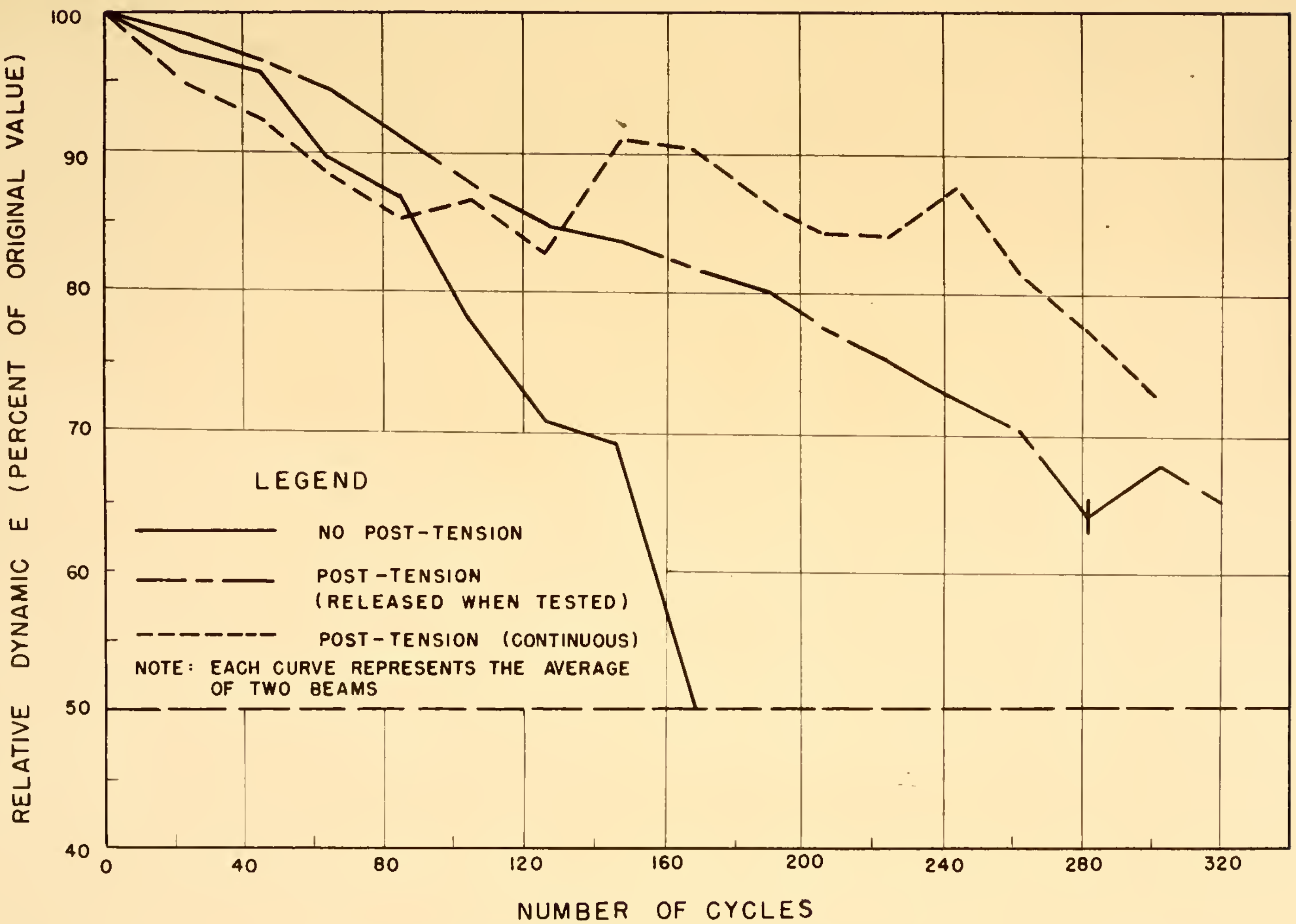

FIGURE 14 THE EFFECT OF FREEZING AND THAWING ON THE DYNAMIC MODULUS OF ELASTICITY. (MIX I A)

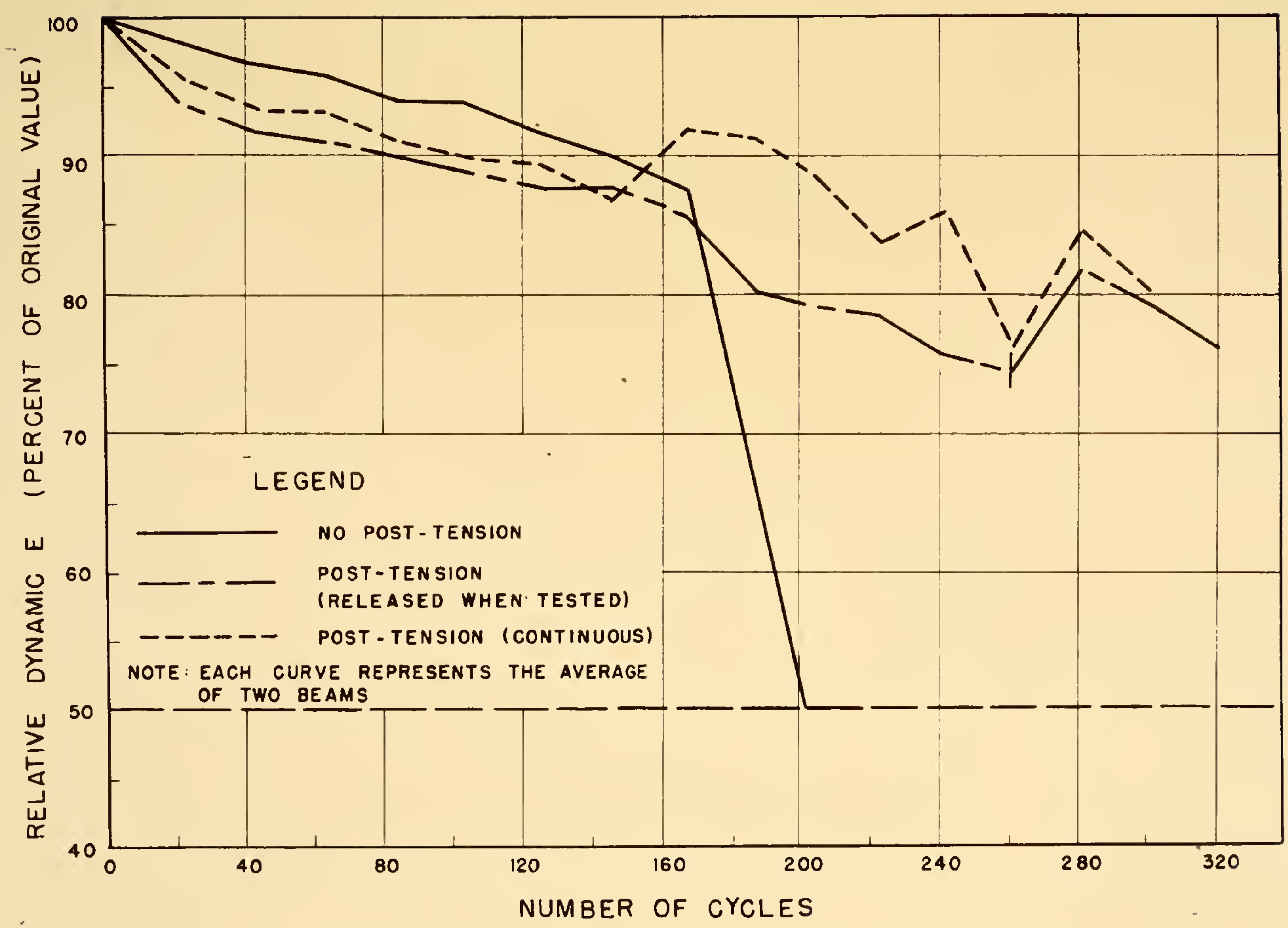

FIGURE 15 THE EFFECT OF FREEZING AND THAWING ON THE DYNAMIC MODULUS OF ELASTICITY. (MIX I B)

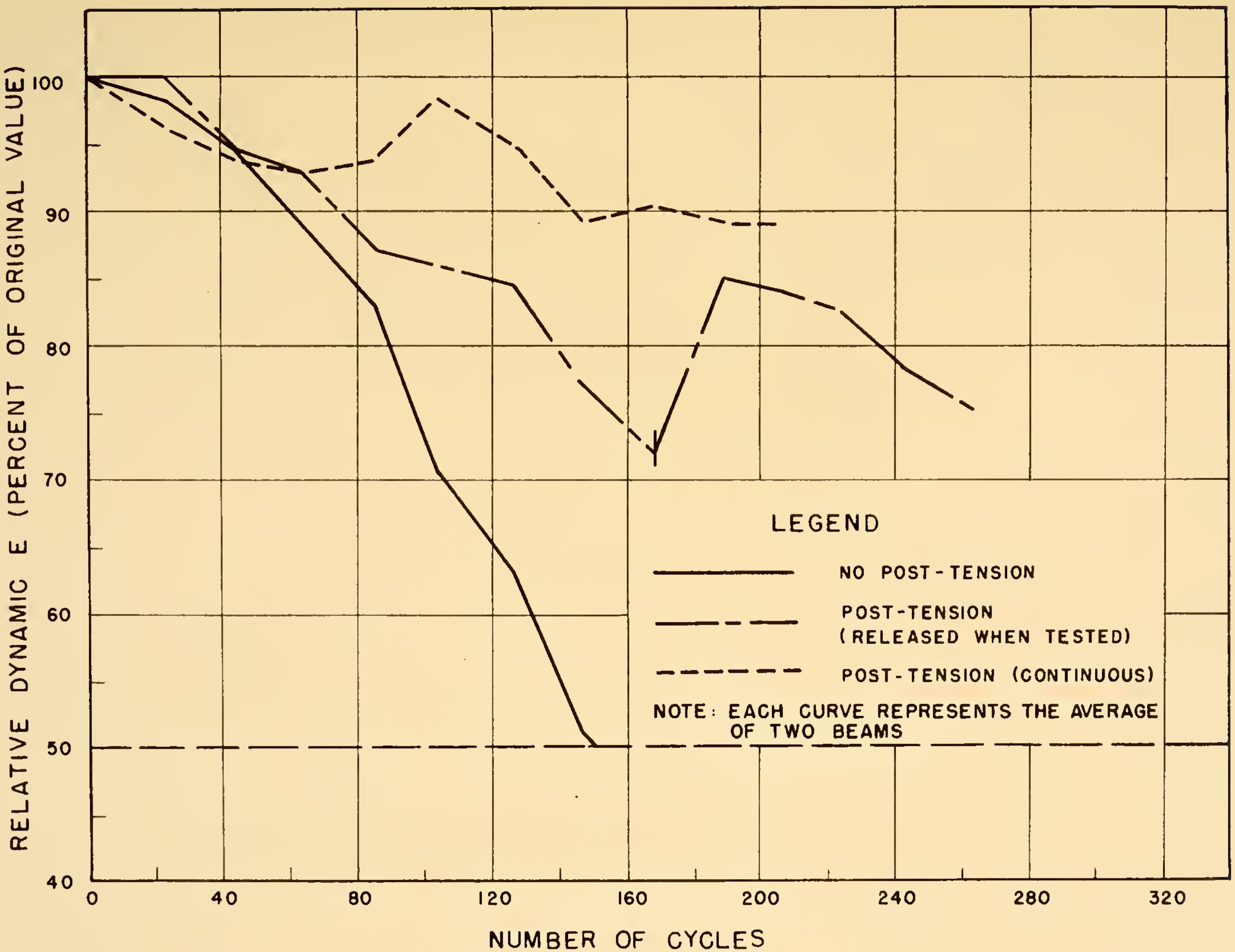

FIGURE 16 THE EFFECT OF FREEZING AND THAWING ON THE DYNAMIC MODULUS OF ELASTICITY. (MIX IC)

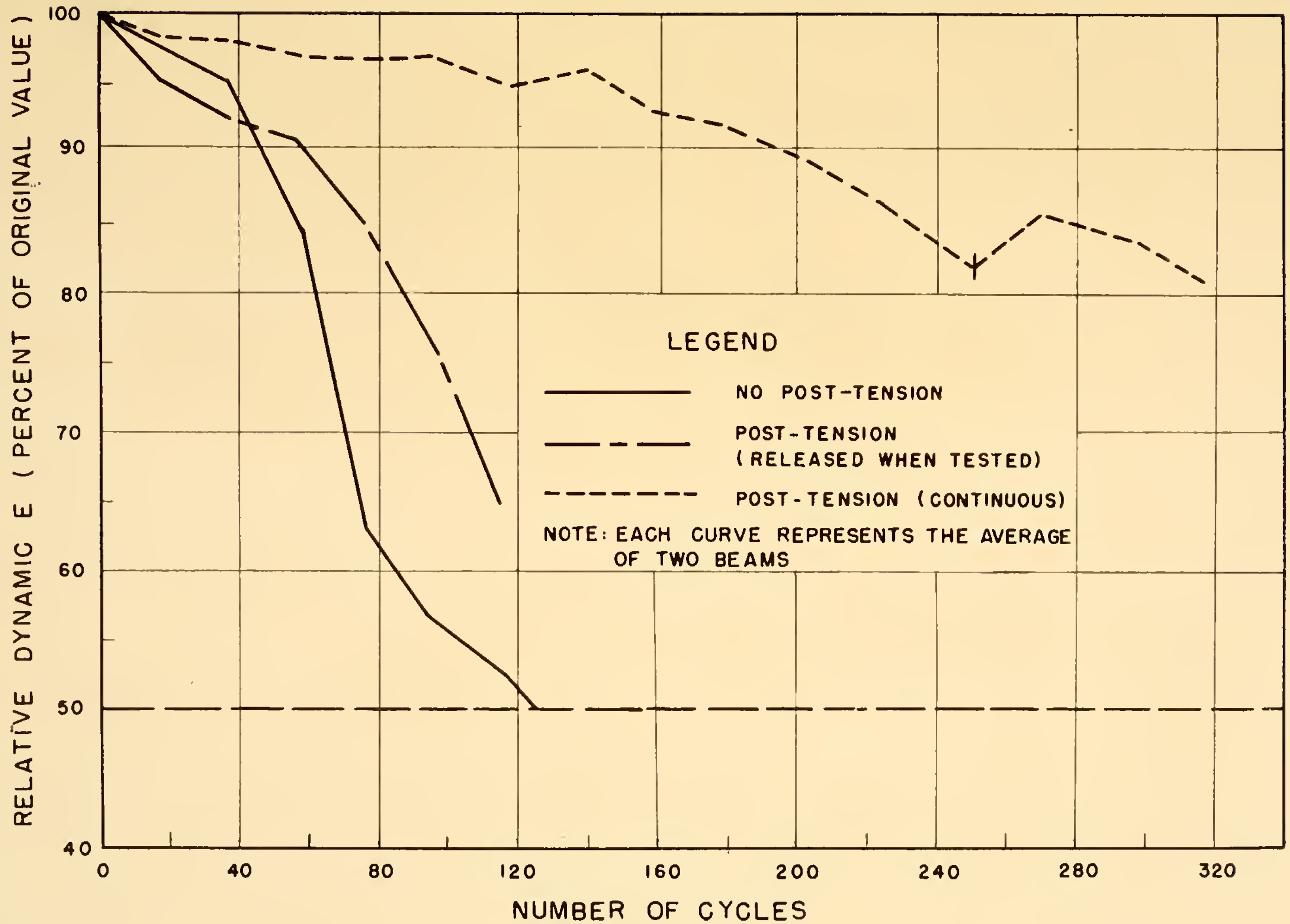

FIGURE 17 THE EFFECT OF FREEZING AND THAWING ON THE DYNAMIC MODULUS OF ELASTICITY. (MIX II A)

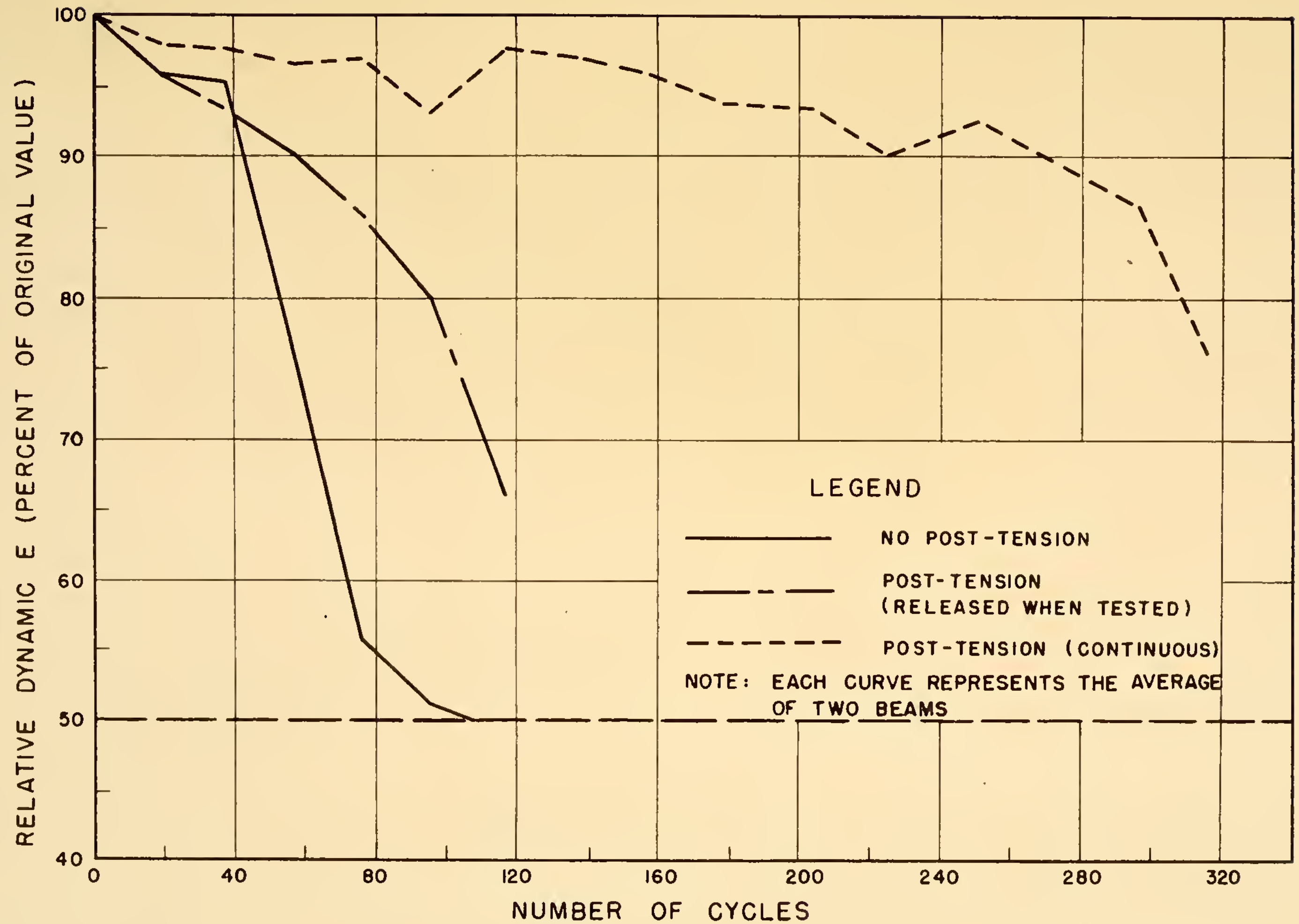

FIGURE 18 THE EFFECT OF FREEZING AND THAWING ON THE DYNAMIC MODULUS OF ELASTICITY. (MIX II B)

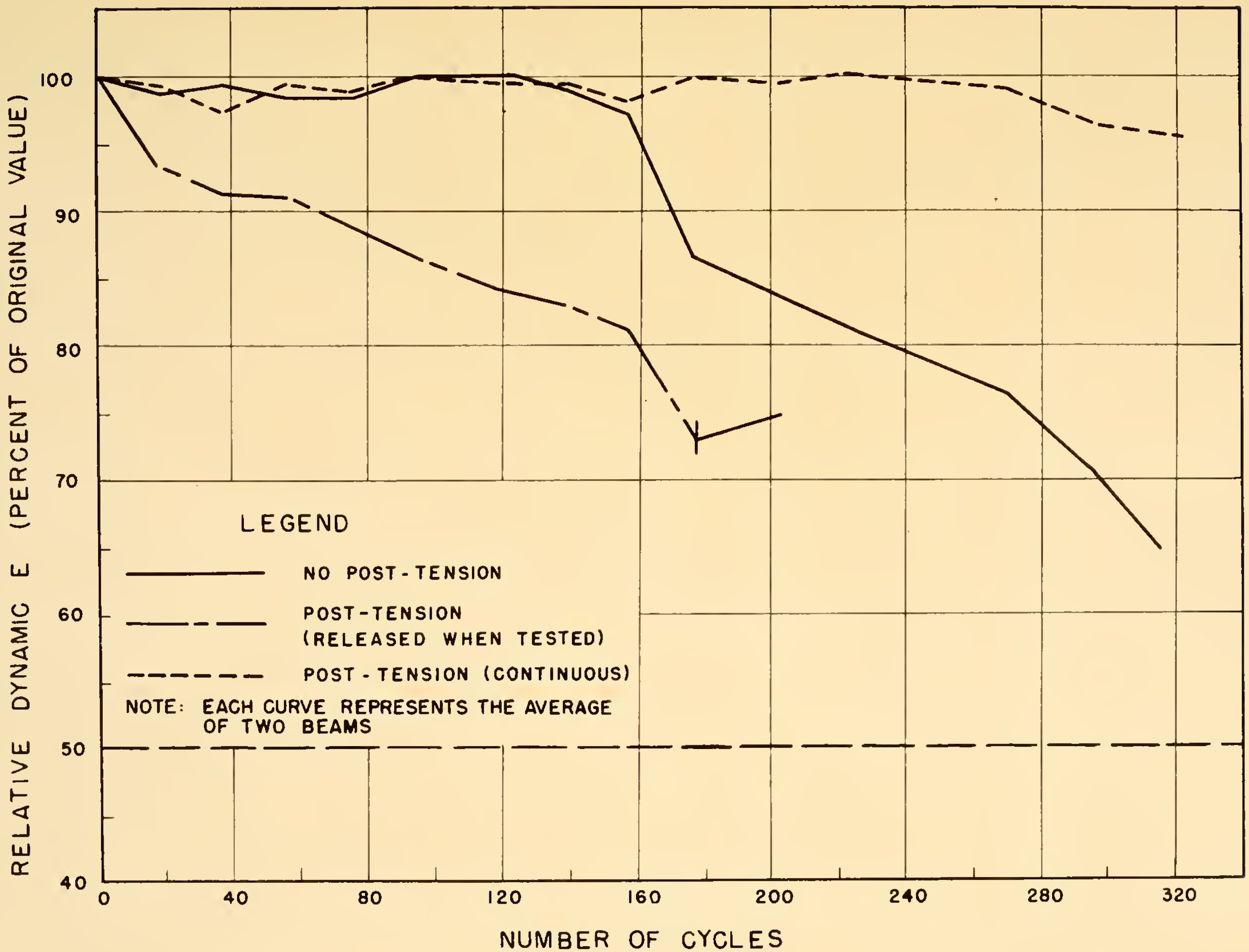

FIGURE 19 THE EFFECT OF FREEZING AND THAWING ON THE DYNAMIC MODULUS OF ELASTICITY. (MIX II C)

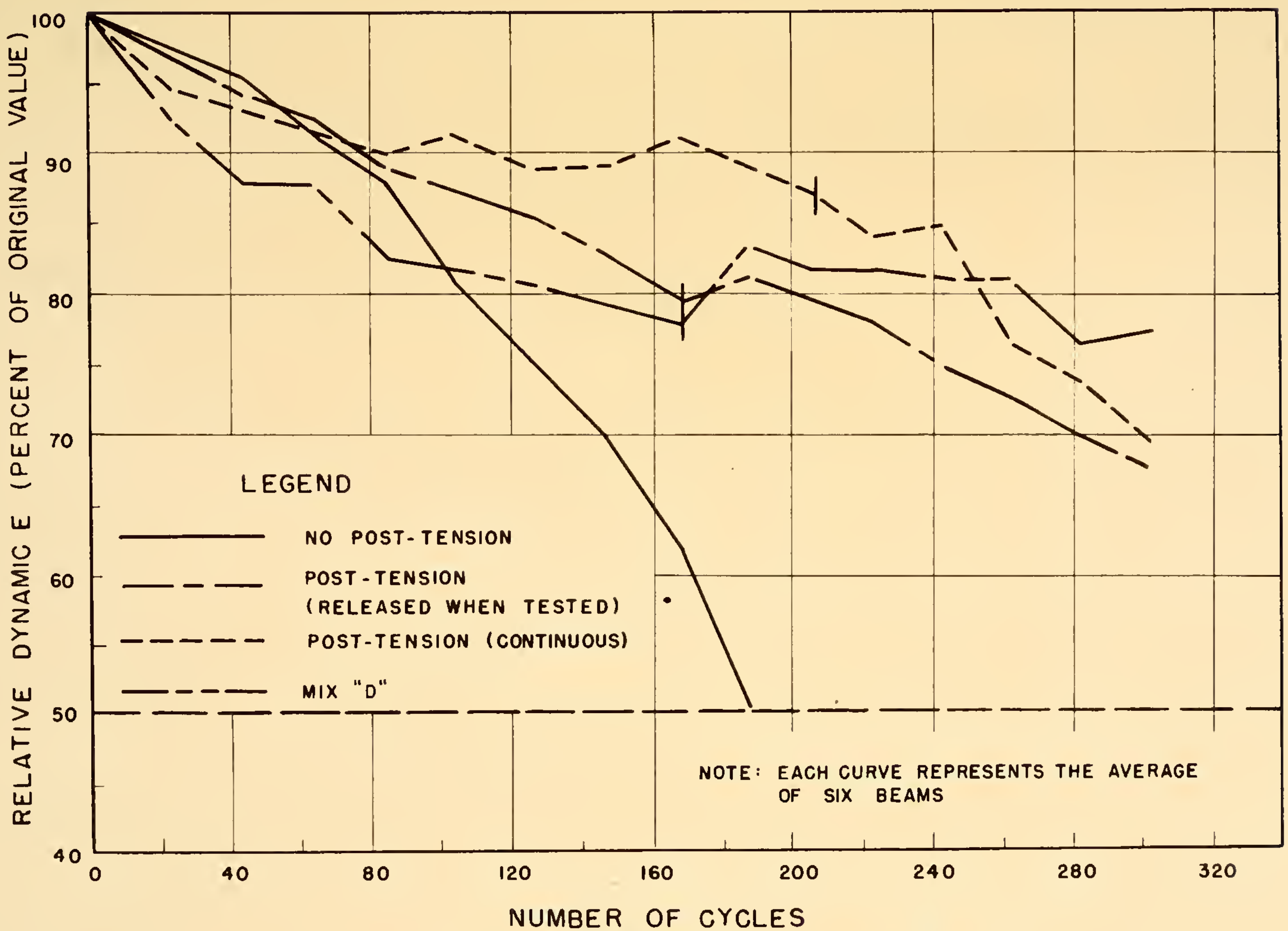

FIGURE 20 THE EFFECT OF FREEZING AND THAWING ON THE DYNAMIC MODULUS OF ELASTICITY. (SERIES I)

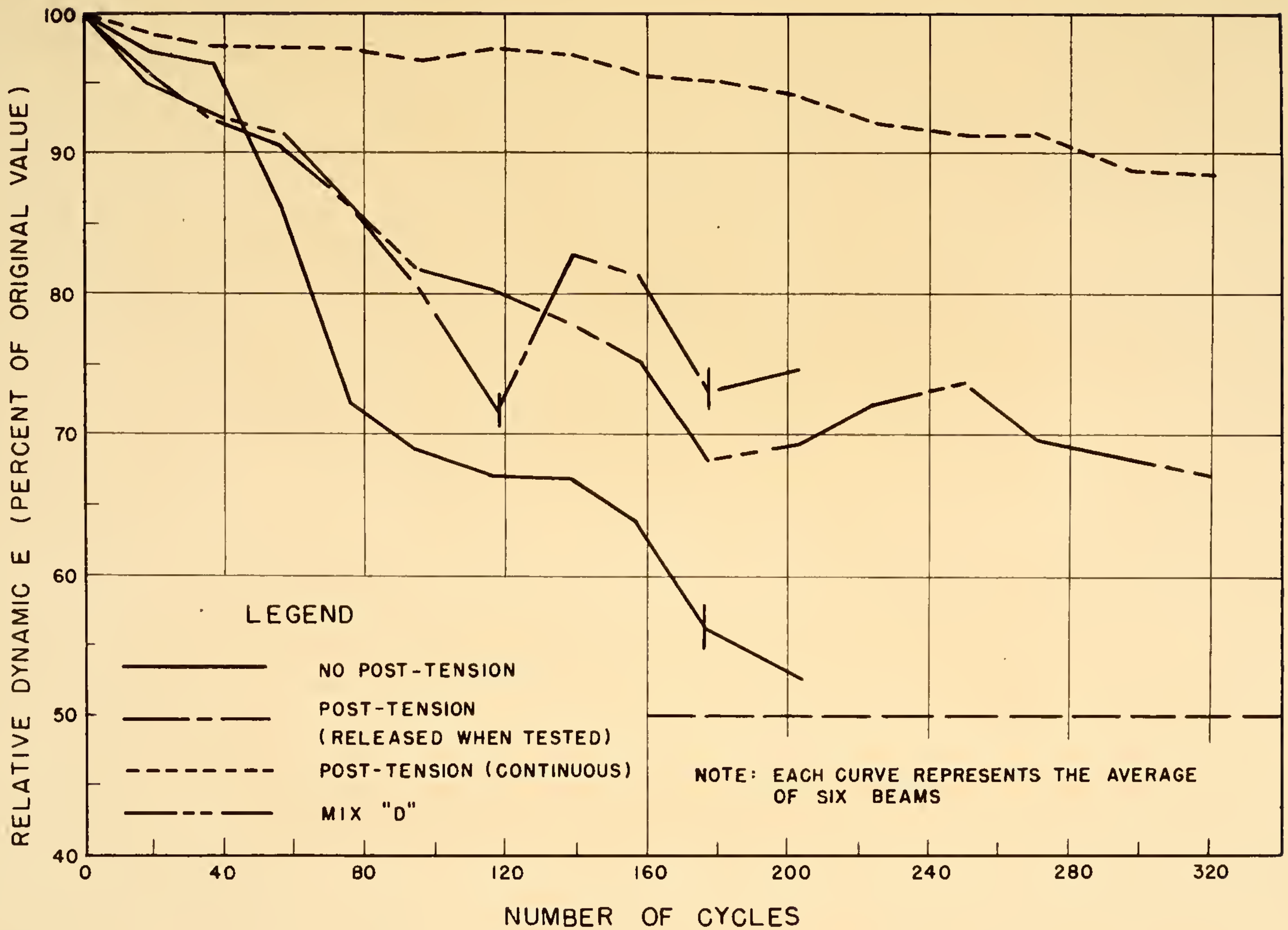

FIGURE 21 THE EFFECT OF FREEZING AND THAWING ON THE DYNAMIC MODULUS OF ELASTICITY. (SERIES II)

the sudden increases in some of the curves.

Table 6 shows the values of the durability factors for the individual beams of series I at 300 cycles of freezing and thawing. The average durability factor for each six similar beams was given.

Table 7 summarizes the results of series II in a similar manner.

Types of Concrete Failure

The decrease in the dynamic modulus of elasticity was measurable in all the specimens tested. In the case of beams numbered 3 and 4 of mixes A, B and C, where the initial prestressing force was applied every time the beams were tested, this failure came at an early stage. In the beams numbered 5 and 6, more freeze-thaw cycles were required to produce this failure. In the latter case, the initial prestressing force was applied before the beginning of the test and was maintained permanently throughout the whole study. As the experiment proceeded, creep in the concrete took place, and the initial prestressing force dropped significantly. A typical failure of the prestressed concrete beams is shown in Figure 22.

In addition to the decrease in the dynamic modulus of elasticity, Walker (12) listed three major classifications of deterioration in concrete due to unsound aggregates. These are (a) pitting and pop-outs, (b) D-line deterioration, and (c) map cracking.

Table 6

DURABILITY FACTORS OF SERIES I BEAMS

AT 300 CYCLES

MIX	BEAM	3000 PSI PLAIN CONCRETE	5000 PSI CONCRETE		
			Plain Concrete	Prestressing Force Released During Testing	Permanently Prestressed Concrete
A	1		27.5		
	2		28.2		
	3			67.6	
	4			54.3	
	5				84.6
	6				60.5
B	1		31.2		
	2		34.7		
	3			79.1	
	4			57.1	
	5				87.9
	6				72.4
C	1		25.7		
	2		24.3		
	3			65.8	
	4			20.1	
	5				60.5
	6				46.1
D	1	67.8			
	2	14.1			
	3	71.0			
	4	86.0			
	5	91.6			
	6	69.5			
Average		66.7	28.6	57.3	68.7

Table 7

DURABILITY FACTORS OF SERIES II BEAMS

AT 300 CYCLES

MIX	BEAM	3000 PSI PLAIN CONCRETE	5000 PSI CONCRETE		
			Plain Concrete	Prestressing Force Released During Testing	Permanently Prestressed Concrete
A	1		50.0		
	2		18.0		
	3			30.1	
	4			28.0	
	5				83.2
	6				82.0
B	1		12.7		
	2		23.3		
	3			33.4	
	4			28.4	
	5				82.0
	6				91.3
C	1		77.0		
	2		63.3		
	3			35.5	
	4			37.3	
	5				95.1
	6				98.0
D	1	61.0			
	2	84.0			
	3	72.0			
	4	55.4			
	5	37.3			
	6	68.0			
Average		63.0	40.7	32.1	88.6

FIGURE 22 A TYPICAL FAILURE OF A
POST-TENSIONED BEAM
SPECIMEN C-3 SERIES I

Pitting is the gradual disintegration due to frost of deleterious pieces of aggregates near the surface of the specimen. Pop-outs take usually a conical shape with the apex being at the aggregate particle. These are caused by rapid disruption of a saturated piece of deleterious aggregate. Pitting and pop-outs were frequent during the experiment. They were mainly caused by the limonite particles in the aggregate.

D-line cracking is caused by the change in volume of coarse aggregate particles breaking the bond with the mortar matrix. D-lines first appear as fine cracks along the free edges of the specimen. These were noted on some of the specimens.

Map cracking is a form of disintegration in which random cracks develop over the entire surface. This kind of failure was not found in this study.

Figure 23 shows samples of pitting, pop-outs, and D-line cracking as indicated.

Discussion of Results

In the analysis of the results of any freezing and thawing test, certain facts should be kept in mind:

1. No generally accepted freezing and thawing test has been developed up to this time. The ASTM specifications list four tentative methods for such tests.

2. The freezing and thawing test cannot establish quantitative information to determine the length of actual

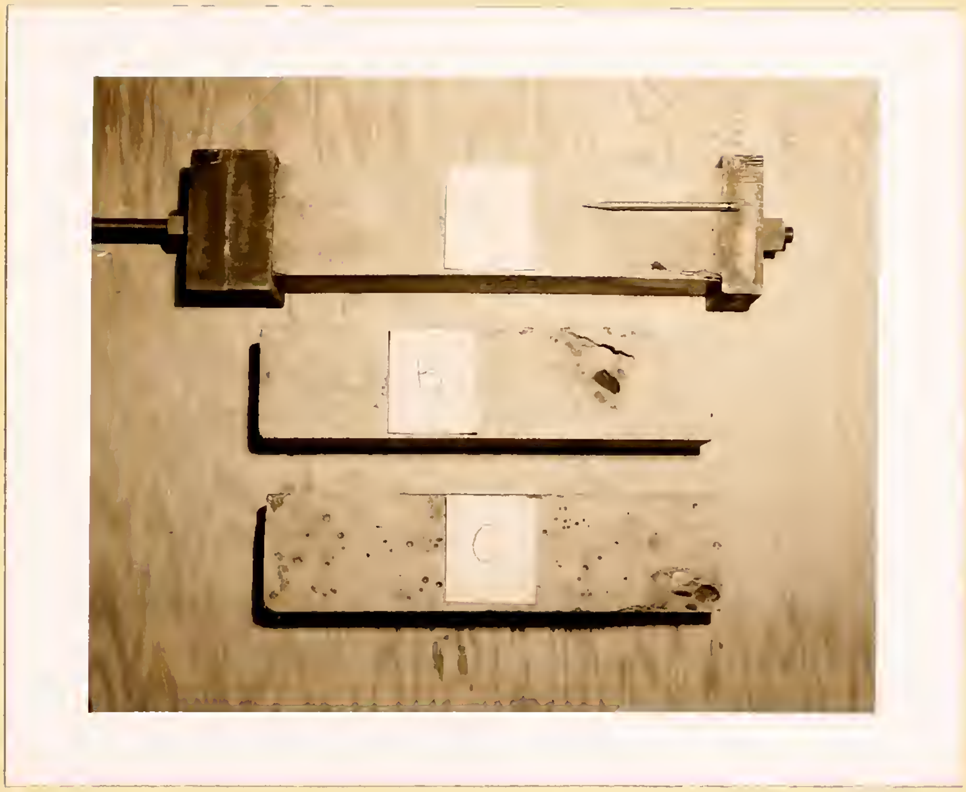

FIGURE 23 THREE TYPES OF FAILURE OF CONCRETE CAUSED BY DELETERIOUS MATERIAL

A D-Line Deterioration After 15 Freeze-Thaw Cycles

B Pop-out After 300 Freeze-Thaw Cycles

C Pitting After 300 Freeze-Thaw Cycles

performance of concrete in the field. The test is expected to give a general idea about the qualitative behavior of the concrete exposed to the natural weathering conditions.

3. At best, the results to be obtained from a freezing and thawing test are comparative data on durability of the test specimens.

4. The accelerated freezing and thawing tests that are performed in the laboratory are generally considered to be very severe tests.

5. The vacuum saturation of the aggregate makes it particularly vulnerable to attack by freezing and thawing. The aggregates that are to be used in concrete in the field are never vacuum saturated.

The freezing and thawing tests specified by the ASTM are meant to be performed on homogeneous beams of concrete. There is no test specified to study the effects of freezing and thawing on reinforced or prestressed concrete. The test used for plain concrete specimens was adopted in this research. The steel bars that were inserted at the center of the beams did not influence the results obtained in this study for the following reasons:

1. The steel bars were used on all beams tested. Thus, the comparative results obtained are considered valid.

2. No bond was developed between the steel and the concrete. A sample beam was tested for its fundamental frequency with the bar in its center, and then the same beam

was tested again with the bar completely removed. The fundamental frequencies measured in both cases were identical. This check was repeated frequently during the various stages of the experiment and the same results were obtained in every check. This means that the fundamental frequency of the concrete was not affected by the unstressed steel bar.

Beams numbered 5 and 6 of mixes A, B and C of both series were tested for the fundamental frequency in a post-tensioned condition. The loading arrangement adopted consisted of a non-bonded steel bar placed axially in the center of the beam and post-tensioned in the standard manner, distribution plates being used at the ends of the beam to transmit the load to the concrete. Steel nuts on the outer side of each end plate maintained the post-tensioning force. This arrangement provided a self-contained system which was tested dynamically in a manner similar to that used for the unstressed concrete. In this case the fundamental frequency of the stressed system, for any beam, was about half the value obtained for the same beam with end plates removed. About 5% of the reduction was due to the stress, the remaining reduction was due to the mass of the end plates and nuts. A detailed theoretical analysis given by Elvery and Furst (13) presented some equations which show this effect of end plates and stress on the fundamental frequency of the specimen. When these beams were subjected to the repeated cycles of freezing and thawing, the fundamental frequency of the system dropped. This indicated the deterioration that occurred in the post-tensioned beams. This deterioration occurred in the concrete and the post-tensioning of the concrete did influence the rate and the nature of the deterioration as will be shown later.

The results of the experiment in all the mixes designated by IA, IB, IC, IIA and IIB show that beams numbered 3 and 4 were more durable than beams numbered 1 and 2. This indicates that post-tensioned concrete, with the stress released every time the test for fundamental frequency was conducted, showed better resistance to freezing and thawing than unstressed concrete made of the same mix. These results may be observed by studying the graphs in Figures 8 to 12, 14 to 18, and 20 as well as Tables 6 and 7.

In mix IIC this pattern was reversed as shown in Figures 13 and 19. The usual behavior for beams numbered 1 and 2, in all the rich mixes, was for the relative modulus of elasticity to show a slight decrease early in the experiment. After a number of cycles, which varied from mix to mix, the relative modulus of elasticity would drop suddenly. However, in mix IIC the drop came after about 300 cycles. At the same time the deterioration of beams numbered 3 and 4 was gradual throughout the experiment. This also explains the fact that the average durability factor for plain concrete was higher than the average durability factor for the post-tensioned concrete in series II as shown in Table 7. In the averages of the dynamic modulus of elasticity plotted in Figure 21, for the groups of six similar beams, the effect of mix IIC is not apparent.

The results of all mixes designated A, B and C in both series show that the continuously post-tensioned beams, which were numbered 5 and 6, were considerably more durable than beams numbered 3 and 4 in which the post-tension was released for modulus measurements and were also better than the unstressed beams numbered 1 and 2.

Elvery and Furst (13) reported a reduction of about five percent in the dynamic modulus of elasticity when the concrete was subjected to a repeated cycle of compressive loading and unloading. This is in complete agreement with the results found in the study.

To summarize, one can definitely conclude that the post-tensioned concrete showed better resistance to freezing and thawing than the unstressed concrete of the same mix.

One of the main objectives of this research was to compare the effect of freezing and thawing on post-tensioned concrete made of a rich mix and ordinary concrete made of a leaner mix. Figures 20 and 21 show the summary of results for series I and II. It is clear that the post-tensioned concrete specimens were more durable than the unstressed, leaner-mix concrete specimens designated as mix D.

It is clear also that the D mix specimens were more durable than unstressed specimens of the richer mixes A, B and C. This result was the main reason for testing series II which confirmed the initial result of series I. These same observations may be made by a study of the average durability factors in Tables 6 and 7. It is believed that the data obtained in this study is too limited to draw a general conclusion in this respect; however, within the range of variables in this experiment, it can be said that the richer mix showed a higher rate of deterioration than the leaner mix. This result is consistent with Powers' hypothesis (8) and is in complete agreement with the results obtained by Bartel (2) and by Walker and Bloem (5).

CONCLUSIONS

Based on the results obtained and within the limitations of the variables studied in this experiment, the following conclusions are drawn:

1. The post-tensioning of concrete improves its effective durability against cyclic freezing and thawing.

2. Continuously post-tensioned concrete, having a minimum ultimate strength of 5000 psi after 28 days is effectively more durable than unstressed concrete having minimum ultimate strength of 3000 psi after 28 days.

3. Continuously stressed concrete is effectively more durable than intermittently stress-released concrete of the same mix; furthermore, in four out of six cases, the latter is apparently more durable than unstressed concrete of the same mix.

4. Ordinary concrete beams made from a rich mix are less durable than ordinary concrete beams made of a leaner mix.

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